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RESEARCH MEMORANDUM

A METHOD OF MEASURING JET THRUST OF TURBOJET ENGINES IN FLIGHT INSTALLATIONS

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NATIONAL ADVISORY COMMITTEE
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A METHOD OF MEASURING JET THRUST OF TURBOJET ENGINES IN FLIGHT INSTALLATIONS

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SUMMARY

Measurement of the jet thrust of a turbojet engine in flight becomes more difficult as the number and complexity of the engine components increase. It is desirable, therefore, that a general correlation of jet thrust be developed which is applicable to a simple direct reading thrustmeter. In view of this need a correlation is presented which is independent of flight conditions and applicable to both nonafterburning and afterburning engines equipped with nonejector type fixed- and variable-area convergent exhaust nozzles.

The general equation used in this correlation was derived from the theoretical jet-thrust equation for a choked convergent nozzle. The data used to verify the correlation were obtained over a range of altitudes from 10,000 to 54,000 feet and a range of flight Mach numbers from 0.4 to 1.1. A thrustmeter based on this equation was installed on an afterburning turbojet engine equipped with a fixed-area convergent exhaust nozzle. The results indicated that a meter based on this correlation would be applicable to a flight installation and that the probable error in thrust measurement would be approximately ± 1.5 percent provided the exhaust-nozzle thrust coefficient is known.

INTRODUCTION

Because of the increasing number of variable components in a turbojet engine that add to the complexity of operation and control, there is a need for an accurate and direct indication of jet thrust in flight installations. A simple instrument that would enable the pilot to dispense with the present system of estimating the thrust output of the engine by the use of engine speed and tail-pipe temperature is desired. An instrument of this type would also be useful in flight or production test installations in which instrumentation must be minimized.

A thrustmeter to be used in flight installations was designed and built by Hesse (refs. 1 and 2) and is based on a correlation of jet

thrust and exhaust-nozzle pressure drop for a nonafterburning engine equipped with a fixed-area exhaust nozzle. The investigation reported herein extends the work reported in references 1 and 2 and puts it on a more general basis through a modification of the correlation presented by Hesse. The modified correlation reported herein results in a generalization of jet thrust which is independent of the flight condition and applicable to nonafterburning and afterburning engines equipped with either fixed or continuously variable area exhaust nozzles. The correlation applies, however, only to engines equipped with convergent exhaust nozzles that are choked at the nozzle outlet.

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Data for this investigation were obtained in the NACA Lewis altitude chambers over a range of altitudes from 10,000 to 54,000 feet and a range of flight Mach numbers from 0.4 to 1.1. Data from two afterburning and two nonafterburning engines, all of which were equipped with convergent exhaust nozzles, are presented herein.

ANALYSIS

The general jet-thrust equation, upon which the jet-thrust correlation presented herein is based, is derived as follows (see list of symbols in the appendix):

$$F_{j,i} = \frac{w}{g} V_n + A_n(p_n - p_0) \tag{1}$$

or

$$F_{j,i} = \gamma A_n p_n M_n^2 + A_n(p_n - p_0) \tag{2}$$

For critical flow in the nozzle,

$$M_n = 1.0 \quad \text{and} \quad p_n = P_9 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} \tag{3}$$

substituting equations (3) into equation (2) and rearranging yield

$$\frac{F_{j,i}}{A_n} = \gamma P_9 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} + P_9 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} - p_0 = (\gamma + 1)\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} P_9 - p_0 \tag{4}$$

For a range of temperatures from 1400° to 4000° R and a range of fuel-air ratios from 0.02 to stoichiometric, the corresponding range of specific-heat ratios is from 1.25 to 1.34. For $\gamma = 1.25$ equation (4) becomes

$$\frac{F_{j,i}}{A_n} = 1.24P_9 - p_0$$

and for $\gamma = 1.34$ equation (4) becomes

$$\frac{F_{j,i}}{A_n} = 1.265P_9 - p_0$$

Because a small variation of the constant in the thrust equation results from the wide range of specific-heat ratios, a constant value may be employed. The following thrust equation will be used in this report:

$$\frac{F_{j,i}}{A_n} = 1.25P_9 - p_0 \tag{5}$$

Equation (5) defines the theoretical value of jet thrust. However, in the actual case, the measured jet thrust will be less than the theoretical value because: (1) The flow area at the vena contracta is less than the measured exhaust-nozzle area, and (2) the actual jet velocity is less than the ideal jet velocity. Therefore, if the ratio of actual to theoretical jet thrust (C_j) is incorporated in equation (5) the working correlation equation becomes

$$F_{j,m} = C_j F_{j,i} = C_j A_n (1.25P_9 - p_0) \tag{6}$$

or

$$\frac{F_{j,m}}{A_n} = C_j (1.25P_9 - p_0) \tag{7}$$

The value $1.25P_9 - p_0$, which will be referred to as the "nozzle pressure-drop parameter," was calculated for all engines; and the measured jet thrust was correlated with this parameter.

APPARATUS

Test Installations

The turbojet engines which are designated A, C, and D were installed in a Lewis altitude test chamber. A schematic diagram of a typical engine installation in an altitude chamber is shown in figure 1(a). Jet thrust of the engine was measured with a null-type air-balanced diaphragm.

Turbojet engine B was installed in the Lewis altitude wind tunnel. A typical wind-tunnel installation is shown in figure 1(b). The engine was mounted on a wing section with a ram pipe attached to the engine inlet. Jet thrust was measured with the tunnel balance-scale system. A listing of the engines and exhaust nozzles investigated is presented in the following table:

Engine	Jet thrust class, lb	Exhaust nozzle
A	5000	Fixed conical
B	7000	Fixed conical
C	5000 + augmentation	Two-position clam shell
D	5000 + augmentation	Continuously variable clam shell

Instrumentation

Engine-inlet total-temperature and -pressure rakes together with exhaust-nozzle-lip static-pressure probes were installed to determine flight conditions. A ram recovery factor of 100 percent was assumed. Water-cooled exhaust-nozzle-inlet total-pressure rakes were installed in each engine. The locations of the instrumentation stations are shown in figure 1(a).

Thrustmeter

A thrustmeter, incorporating the nozzle pressure-drop parameter, was designed and installed to measure the jet thrust of an afterburning turbojet engine which was equipped with a fixed-area exhaust nozzle and under investigation in a Lewis altitude chamber. A schematic diagram of the thrustmeter is shown in figure 2. Total-pressure instrumentation was located at station 5 because of the high temperatures encountered at station 9 during afterburning operation. The pressure relay was set to adjust P_5 to equal $1.25P_9$. A further description of the details of the thrustmeter is given subsequently. A sketch of the integrating total-pressure rake used in conjunction with the thrustmeter is also shown in figure 2.

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RESULTS AND DISCUSSION

Jet-Thrust Correlation

Inspection of the jet-thrust equation (7) indicates that for engines equipped with fixed-area exhaust nozzles, a correlation of jet thrust with the nozzle pressure-drop parameter should be possible for all flight conditions provided the exhaust nozzle is choked and the nozzle thrust coefficient is essentially constant.

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The correlation of jet thrust with the nozzle pressure-drop parameter is shown in figure 3 for engines A and B on which fixed-area, convergent, conical exhaust nozzles were installed. It is evident that jet thrust generalizes for all flight conditions and moreover that the relationship between nozzle pressure-drop parameter and thrust is linear. The jet-thrust equation defines the slope of the curve as being equal to the product of the measured area of the exhaust nozzle and the nozzle thrust coefficient. The thrust coefficients for the exhaust nozzles of engines A and B are 0.98 and 0.97, respectively. A comparison of these correlations with those presented in references 1 and 2 reveals that the use of the nozzle pressure-drop parameter $(1.25P_9 - p_0)$ in place on the nozzle pressure drop $(P_9 - p_0)$ eliminates the need for an altitude correction.

Engine C was normally equipped with a two-position clam-shell-type exhaust nozzle to facilitate both afterburning and nonafterburning operation. However, during the investigation of engine C, two fixed-area, conical exhaust nozzles, which simulated the two-position nozzle, were used for the two modes of operation. From the jet-thrust equation, $F_{j,m} = C_j A_n (1.25P_9 - p_0)$, it is evident that a change in exhaust-nozzle area would result in a change in the slope of the thrust curve. The jet-thrust correlation for engine C (fig. 4) indicates that opening the exhaust nozzle for afterburning operation increased the slope of the thrust curve.

A comparison of engines A, B, and C on the basis of jet thrust per unit of measured exhaust-nozzle area correlated with nozzle pressure-drop parameter is shown in figure 5. When the data are plotted in this manner, the slope of each curve is numerically equal to the thrust coefficient. The data for all the nozzles fall within ±2 percent of a mean line with a slope of 0.97.

This generalization readily lends itself for application to engines equipped with continuously variable area exhaust nozzles. A correlation of jet thrust per unit of measured exhaust-nozzle area for engine D, equipped with a variable-area clam-shell-type exhaust nozzle, resulted in a generalization of jet thrust for all flight conditions as shown in figure 6. The slope of the thrust curve is equal to the thrust coefficient, which in this case is 0.95.

Application of Correlation to Flight Installations

The maintenance of instrumentation at the exhaust-nozzle inlet is difficult during afterburning operation of a turbojet engine because of the high temperatures encountered. However, it has been found that the correlation of jet thrust with nozzle pressure-drop parameter ($1.25P_9 - p_0$) can also be obtained by the substitution of turbine-outlet total pressure (P_5) and the afterburner total-pressure loss for the exhaust-nozzle-inlet total pressure. Of course, the total-pressure loss associated with afterburner operation would have to be determined from a calibration of the engine. Because a pressure multiplying device is a necessary part of any thrustmeter incorporating the nozzle pressure-drop parameter, the afterburner total-pressure loss can be readily included by adjusting the pressure multiplier such that its output is $1.25P_9$ when its input is P_5. For efficient afterburning in a turbojet engine equipped with a two-position exhaust nozzle, burning is restricted to a narrow range of fuel-air ratios; and, for this case, a constant afterburner total-pressure-loss correction may be employed without appreciably affecting the accuracy of the data. However, on an engine equipped with a continuously variable area exhaust nozzle, a wide range of afterburner fuel-air ratios may be encountered; and the variation of afterburner total-pressure loss with fuel-air ratio or exhaust-nozzle area ratio must be considered. For engine D, figure 7 shows the afterburner total-pressure loss as a function of the ratio of measured to maximum exhaust-nozzle area. Since a thrustmeter for an engine equipped with a continuously variable area exhaust nozzle would always require an area correction, the variation of afterburner total-pressure loss with area ratio could also be readily incorporated into the system. If, for the case illustrated, a constant value of afterburner total-pressure loss of 0.076 was assumed, an additional error of ±2 percent would be introduced into the thrust measurement by the variation of the burner total-pressure loss with nozzle area ratio.

A thrust meter utilizing the nozzle pressure-drop parameter was installed on an afterburning turbojet engine equipped with a fixed-area conical exhaust nozzle. The total-pressure survey was taken at the turbine outlet instead of at the exhaust-nozzle inlet. The turbine-outlet total pressure (P_5) was then adjusted to the exhaust-nozzle-inlet total pressure (P_9) by taking the afterburner total-pressure loss into account with the pressure multiplier. A constant value of 12 percent total-pressure loss in the afterburner was assumed and, thus, $P_9 = 0.88P_5$. The exhaust-nozzle-outlet static pressure was measured with a nozzle-lip static probe.

The jet thrust measured with the altitude-chamber thrust scale and the value indicated by the thrustmeter are compared in figure 8. The majority of the data fall within ±1.5 percent of a mean line. The slope of the line, which for this case defines the thrust coefficient of the

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exhaust nozzle, is 0.95. The data indicate that, if the thrust coefficient can be accurately determined from an engine calibration, a value of jet thrust could be obtained by means of a thrustmeter within ±1.5 percent. If it is not possible to calibrate the exhaust nozzle, a close approximation of the thrust coefficient could be obtained from previously compiled data on similar exhaust nozzles. However, if a high degree of accuracy is not required, a mean value of thrust coefficient of 0.97 can be assumed with an expected accuracy of ±3 percent of jet thrust.

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CONCLUDING REMARKS

The correlation of jet thrust with an exhaust-nozzle pressure-drop parameter resulted in a linear generalization of jet thrust for all flight conditions. Jet thrust per unit of measured exhaust-nozzle area was correlated with the nozzle pressure-drop parameter, and a single generalization was obtained for all the fixed- and variable-area convergent exhaust nozzles investigated.

A thrustmeter incorporating the nozzle pressure-drop parameter was installed on an afterburning turbojet engine (equipped with a fixed-area convergent exhaust nozzle) which was under investigation in a Lewis altitude chamber. Because of the difficulty in maintaining instrumentation at the exhaust-nozzle inlet during afterburning operation in a flight installation, the exhaust-nozzle-inlet total pressure was replaced by the turbine-outlet total pressure and the afterburner total-pressure loss. The results of this investigation indicate that a meter of this type would be applicable to flight installations and that the probable error in thrust measurement would be approximately ±1.5 percent provided an accurate value of the nozzle thrust coefficient could be obtained.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, November 4, 1953

APPENDIX - SYMBOLS

The following symbols are used in this report:

A	area, sq ft
C_j	jet thrust coefficient
F_j	jet thrust, lb
g	acceleration due to gravity, ft/sec^2
M	Mach number
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
R	gas constant, 53.4 ft-lb/(lb)($^\circ$R)
T	total temperature, $^\circ$R
V	velocity, ft/sec
w	weight flow, lb/sec
γ	ratio of specific heats

Subscripts:

i	theoretical
m	measured
max	maximum
n	nozzle
0	nozzle discharge
5	turbine outlet
9	exhaust-nozzle inlet

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1. Hesse, W. J.: Analysis of Turbojet Engine Thrust in Flight. Proj. TED-PTR-PP-343, Test Pilot Training Div., U.S. Naval Air Test Center (Maryland), July 18, 1951.

2. Hesse, W. J.: A Simple Gross Thrust Meter Installation Suitable for Indicating Turbojet Engine Gross Thrust in Flight. Tech. Rep. No. 2-52, Test Pilot Training Div., U.S. Naval Air Test Center (Maryland), Apr. 3, 1952.

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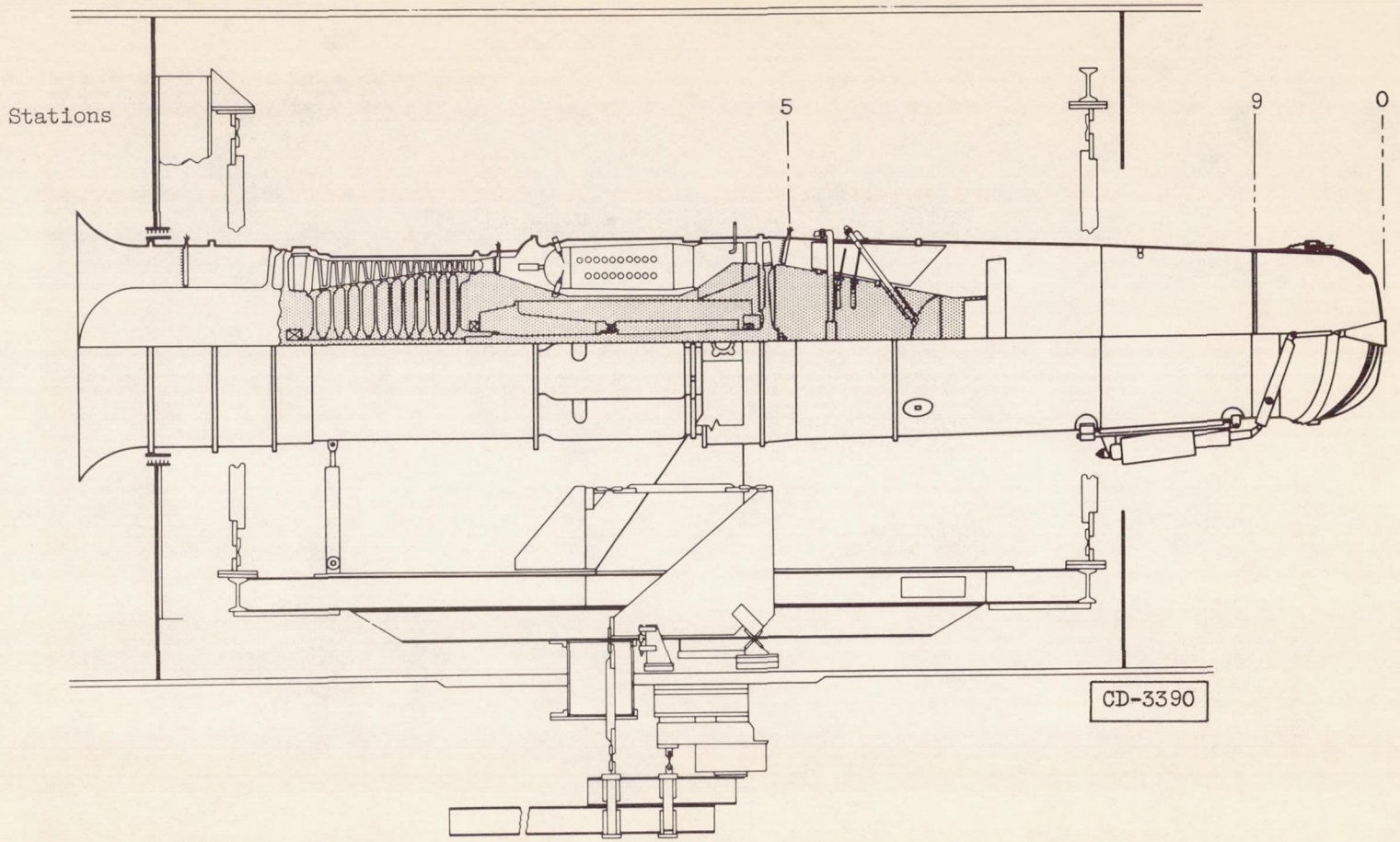

(a) Altitude test chamber.

Figure 1. - Typical engine installations in altitude test facilities.

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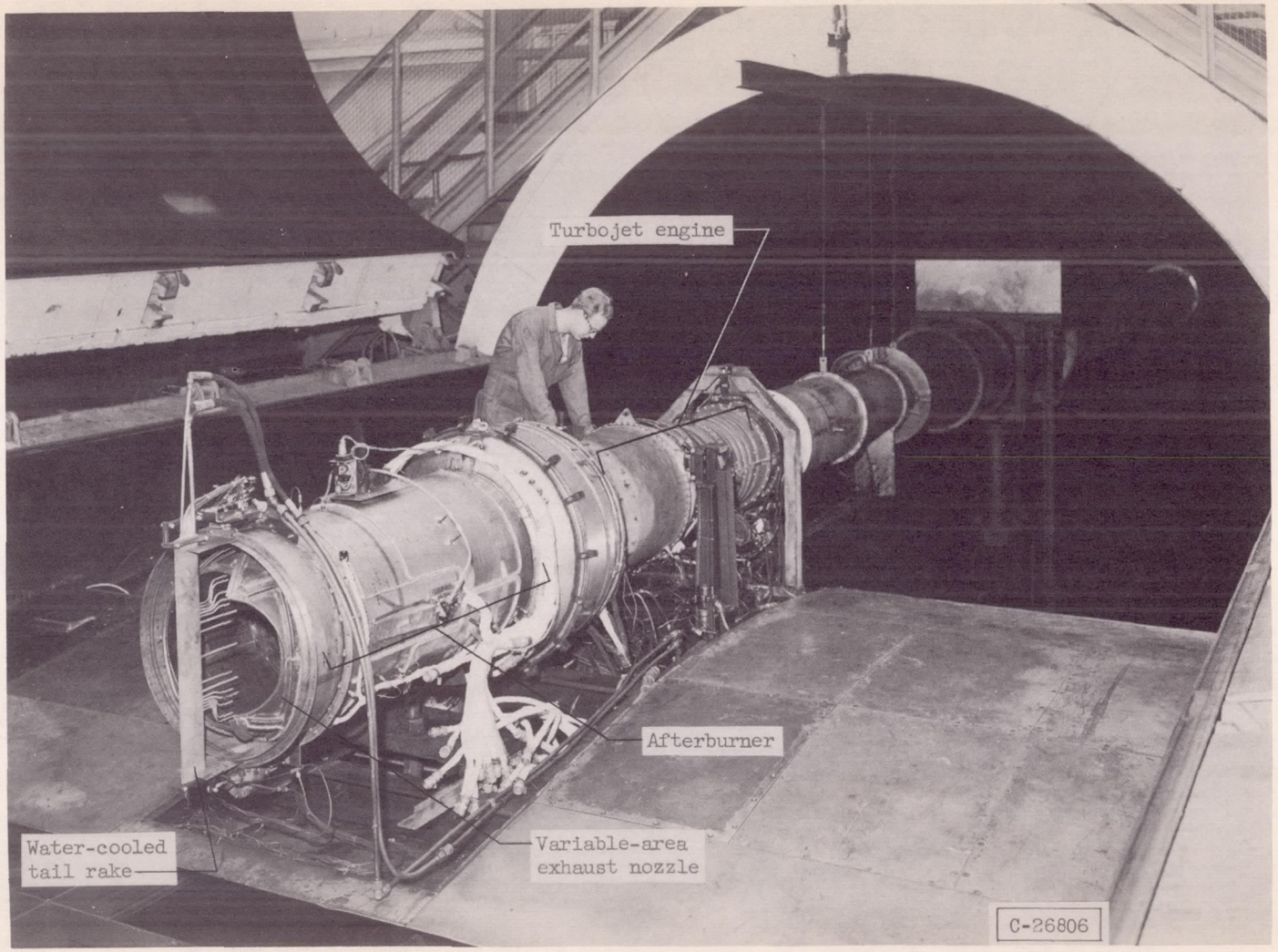

(b) Altitude wind tunnel.

Figure 1. - Concluded. Typical engine installations in altitude test facilities.

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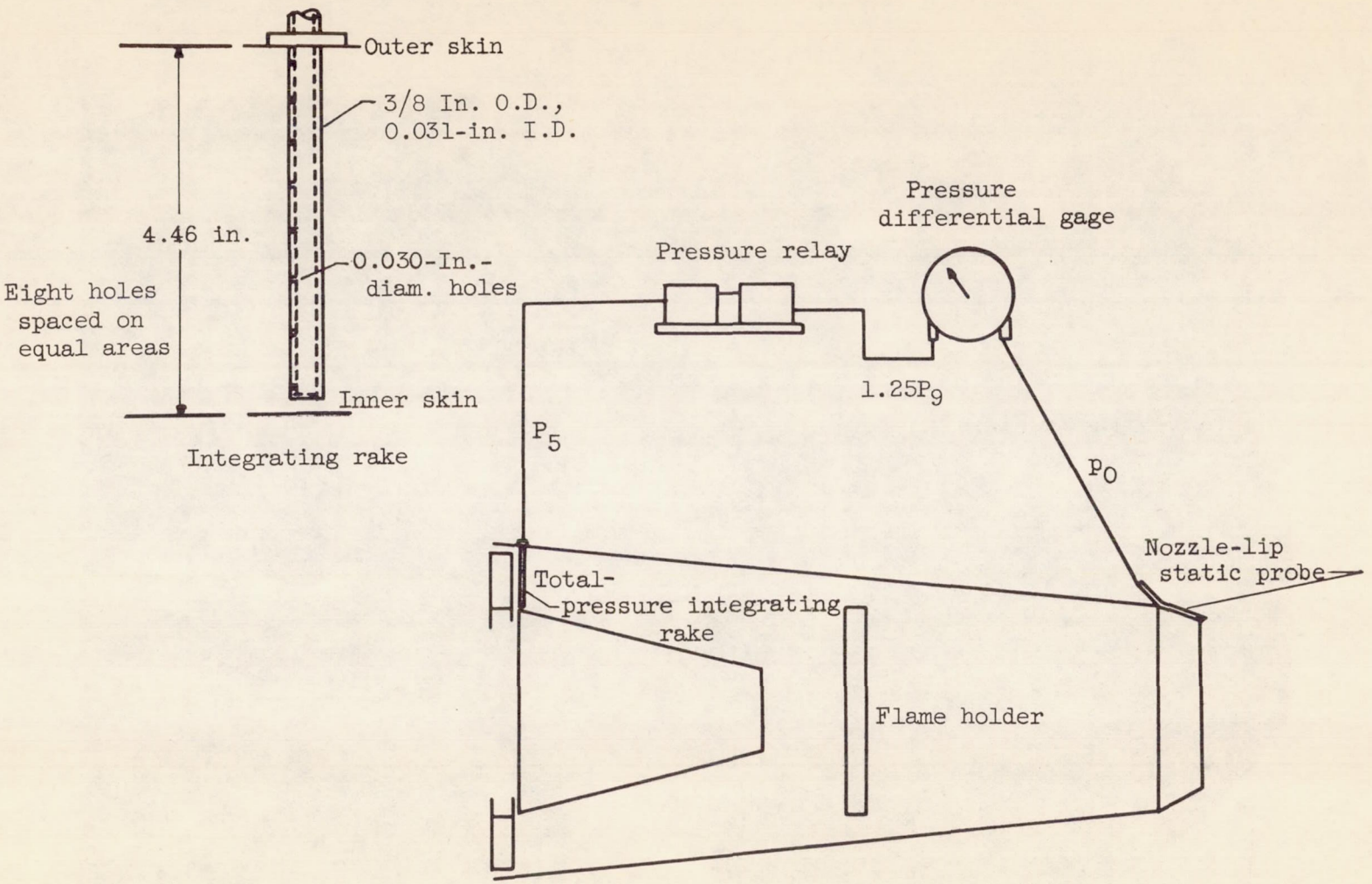

Figure 2. - Schematic diagram of thrust meter installation.

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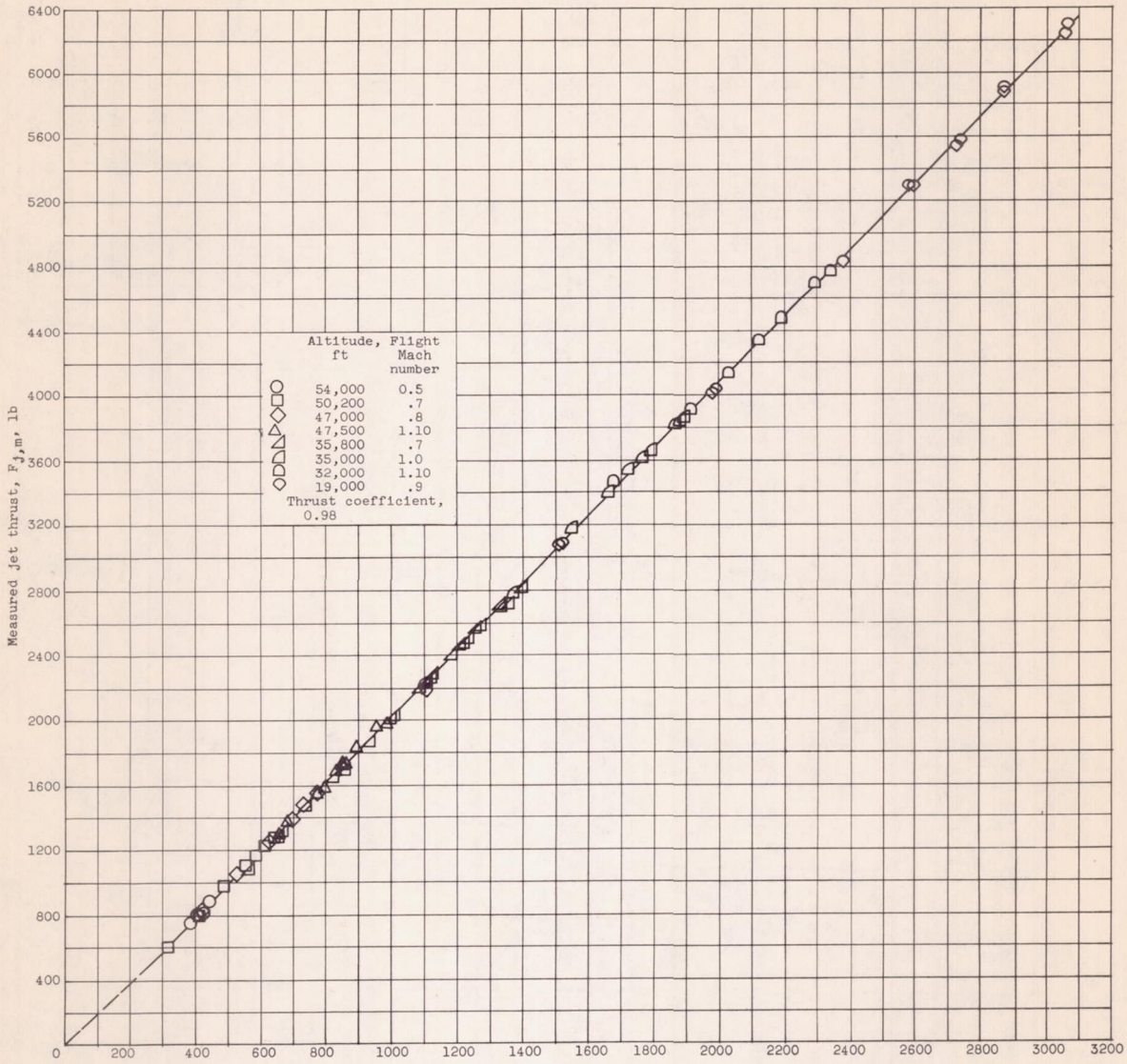
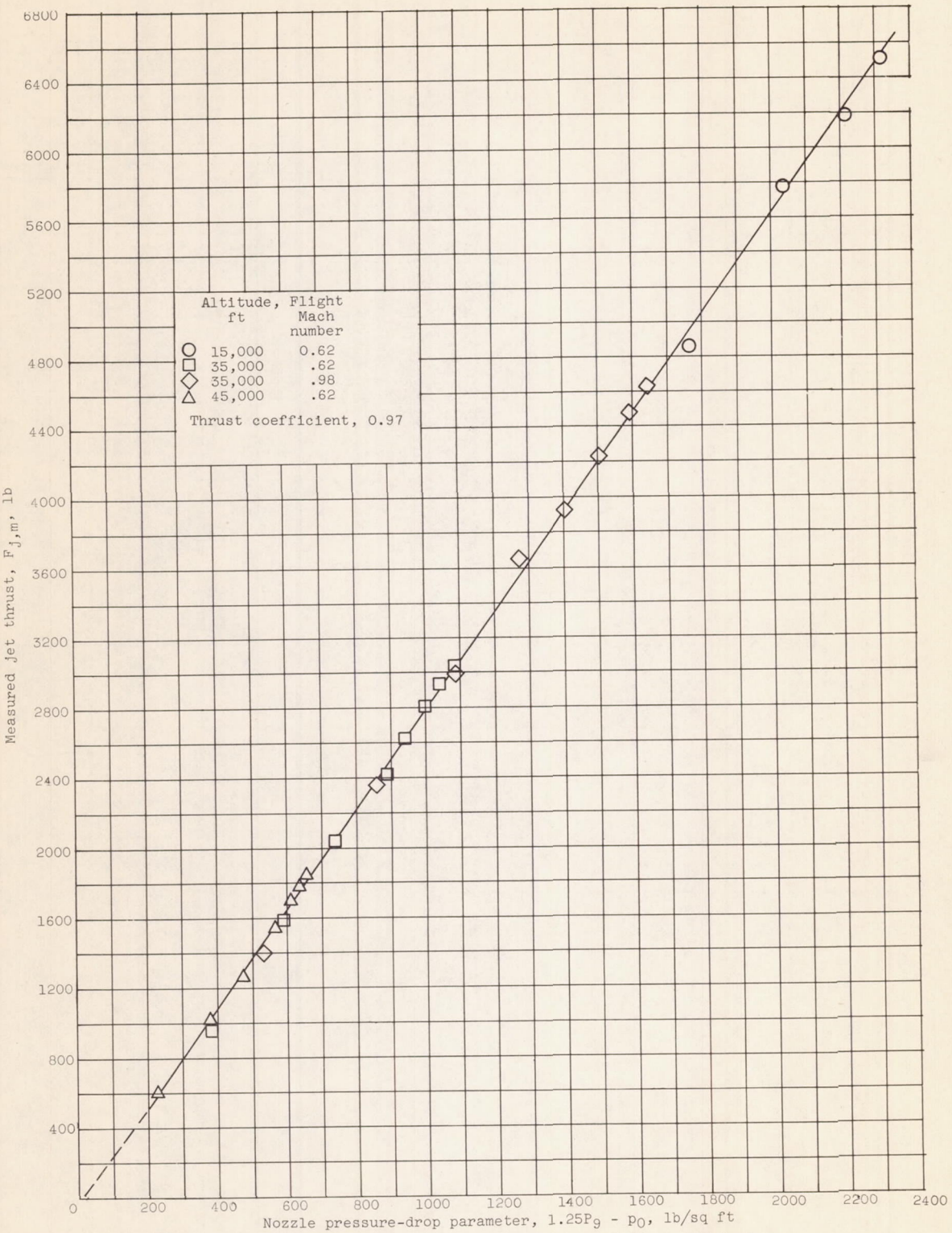


(a) Engine A; measured exhaust-nozzle area, 2.08 square feet.

Figure 3. - Jet-thrust correlations for engines having fixed-area, convergent, conical exhaust nozzles.



(b) Engine B; measured exhaust-nozzle area, 2.93 square feet.

Figure 3. - Concluded. Jet-thrust correlations for engines having fixed-area, convergent, conical exhaust nozzles.

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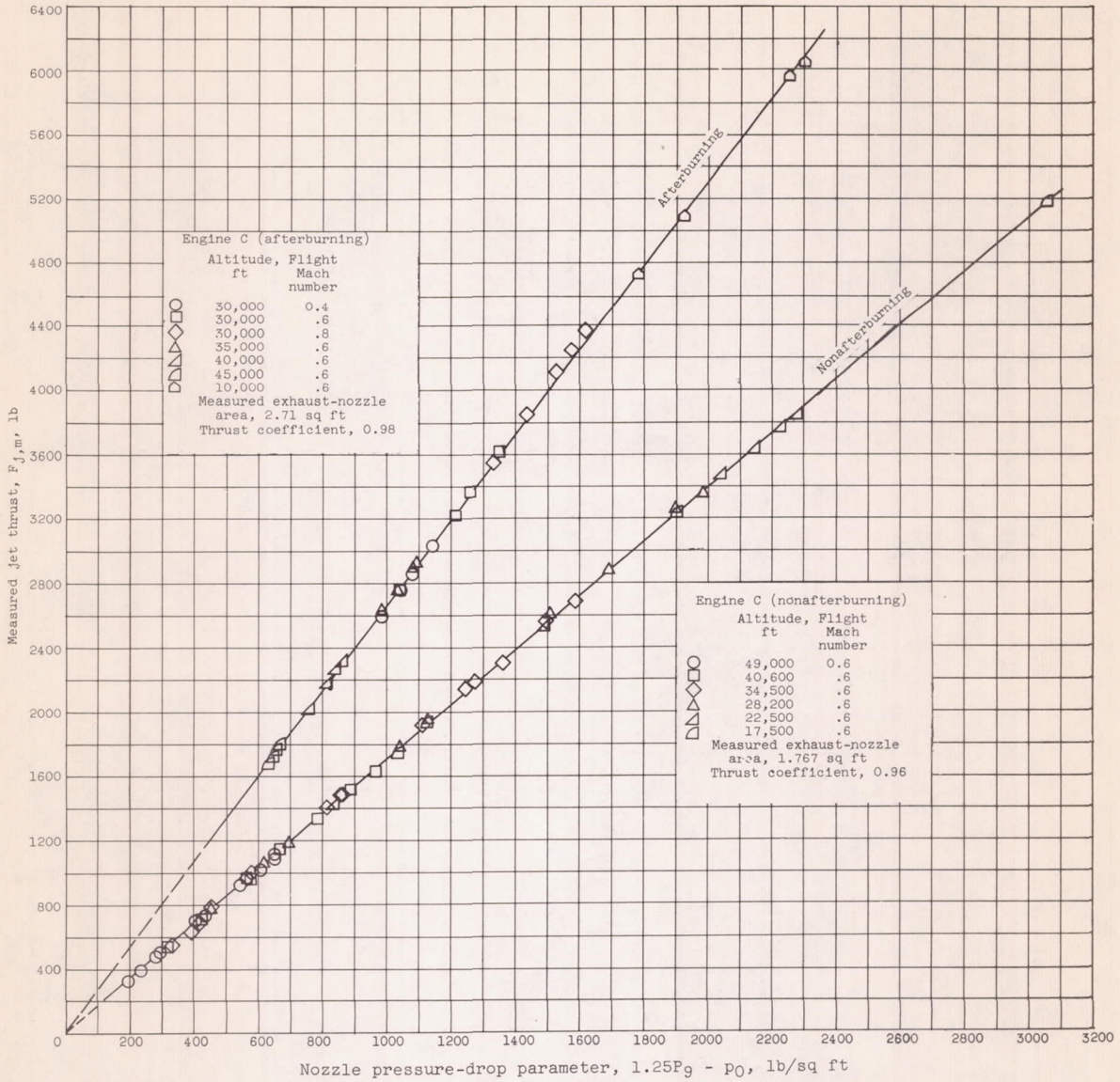

Figure 4. - Jet-thrust correlation for engine C with two fixed-area, convergent, conical exhaust nozzles.

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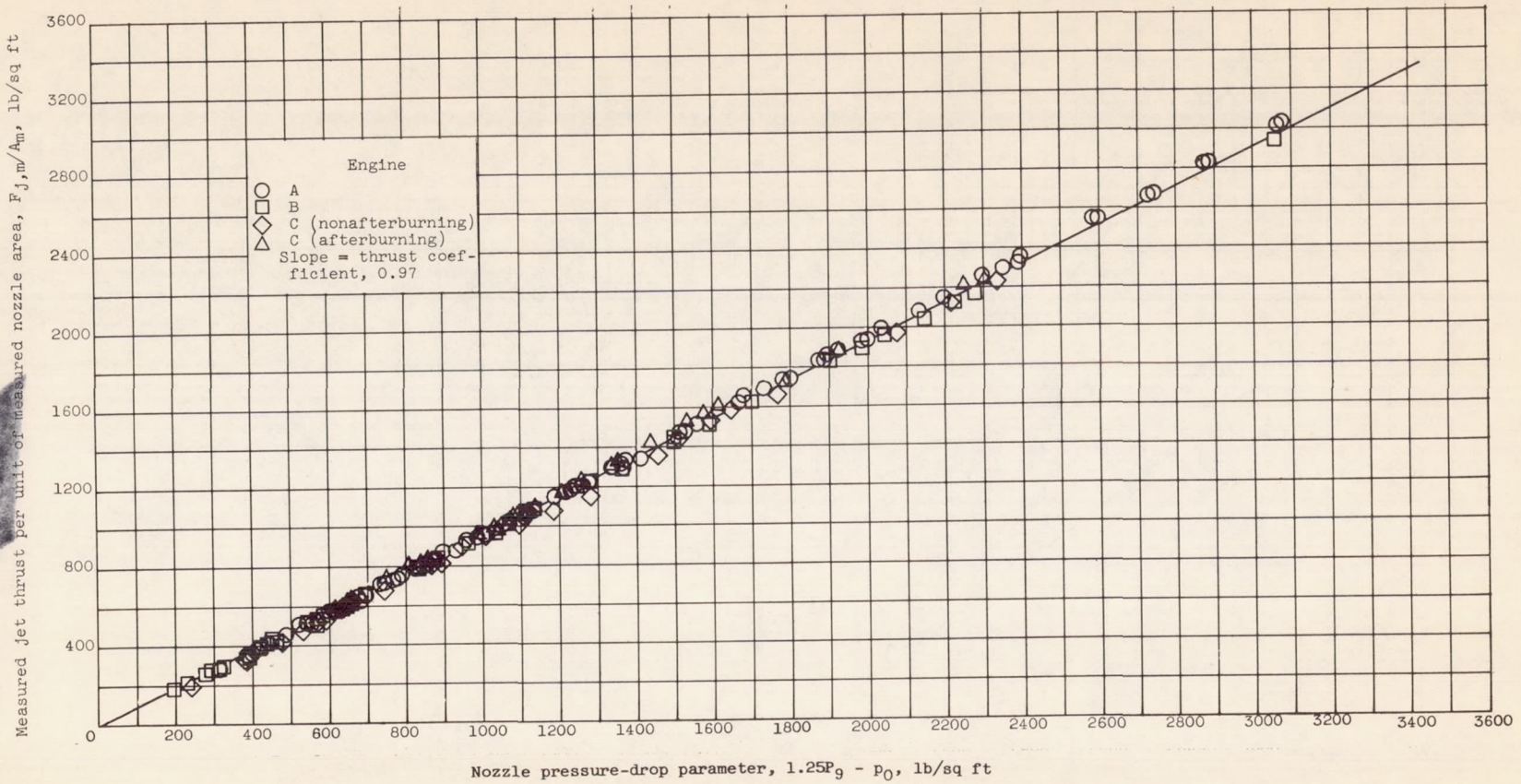

Figure 5. - Correlation of measured jet thrust per unit of measured exhaust-nozzle area for engines A, B, and C.

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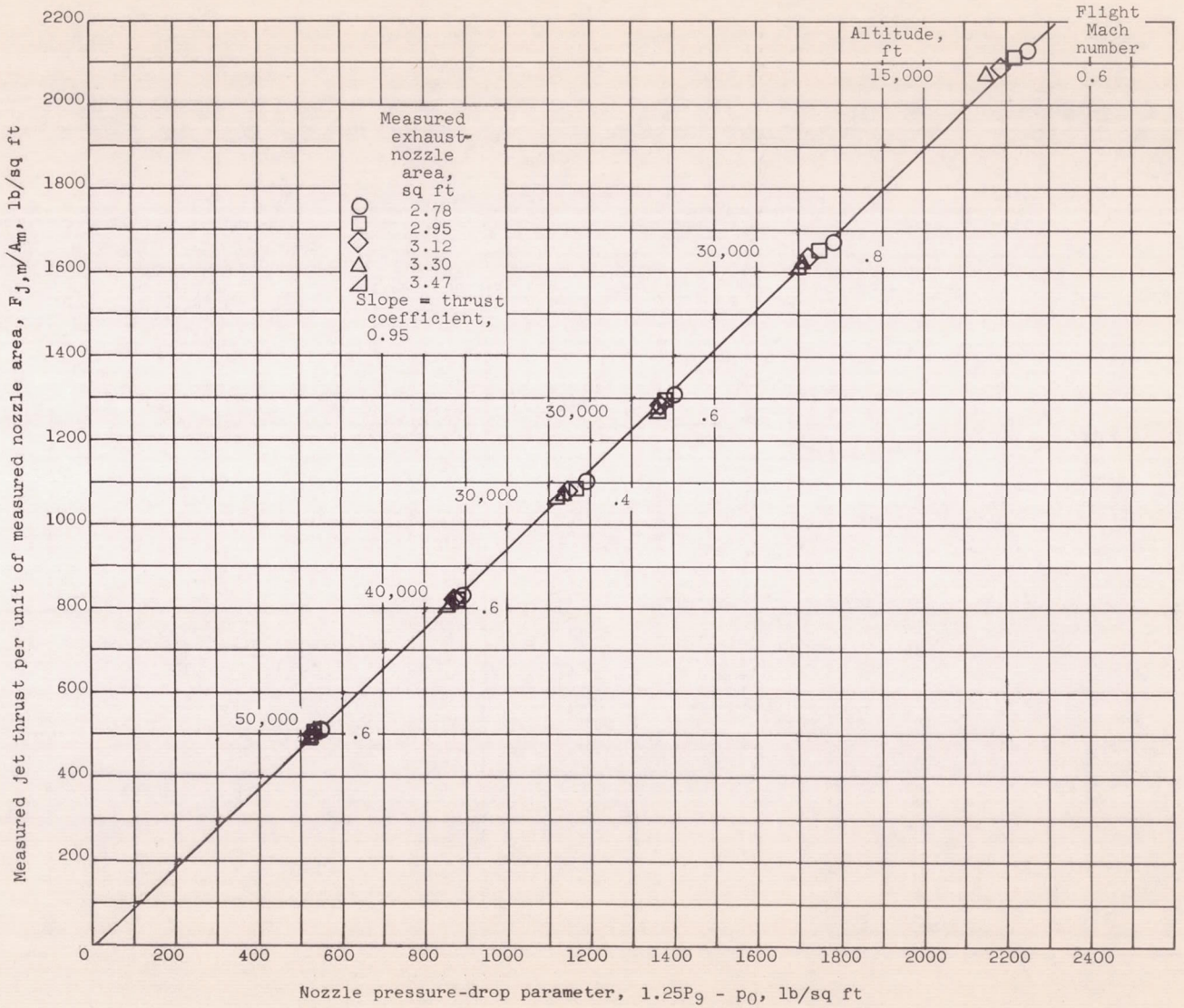

Figure 6. - Correlation of measured jet thrust per unit measured exhaust-nozzle area for engine D, afterburning engine equipped with continuously variable area exhaust nozzle.

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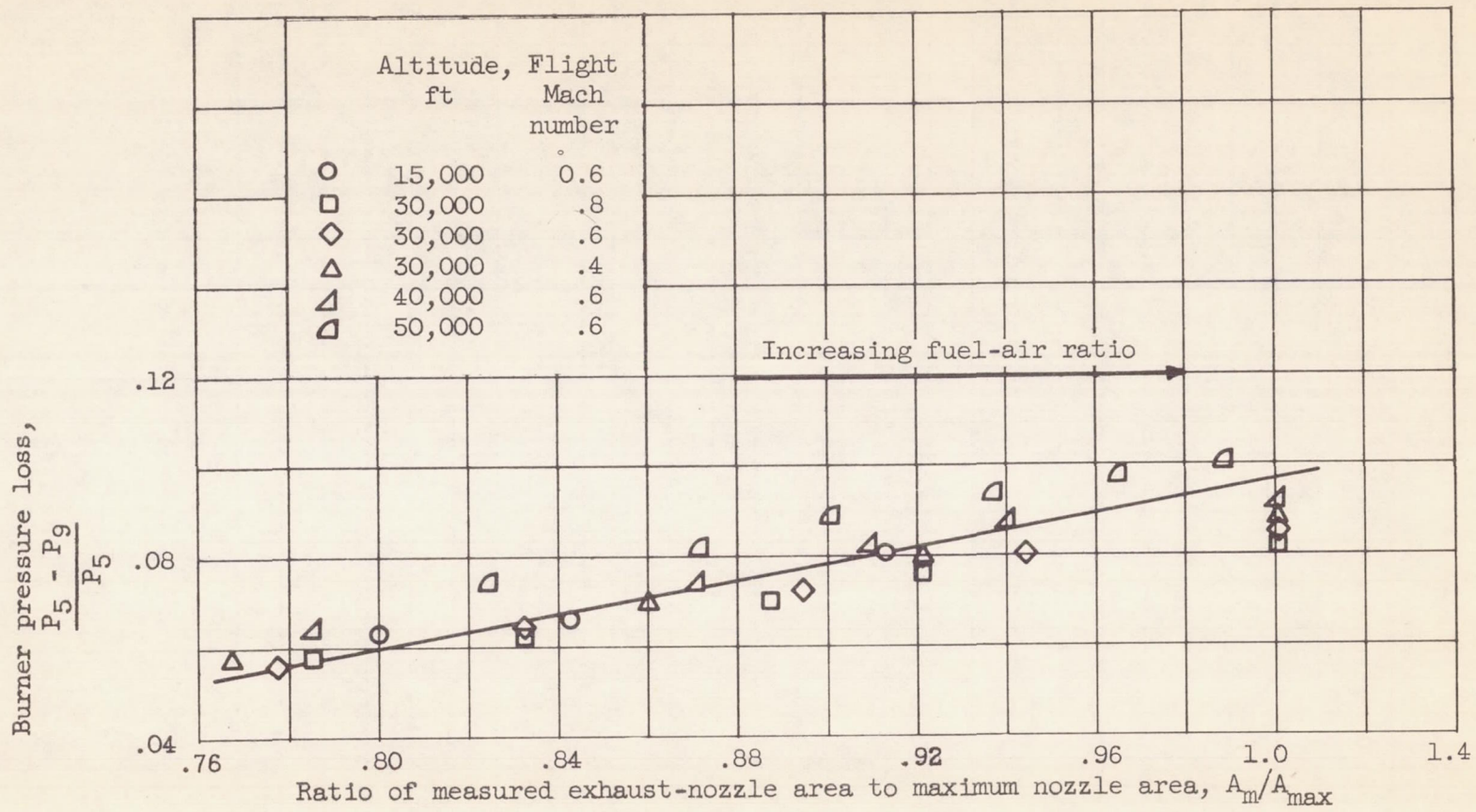

Figure 7. - Variation of afterburner pressure loss with exhaust-nozzle area ratio for engine D.

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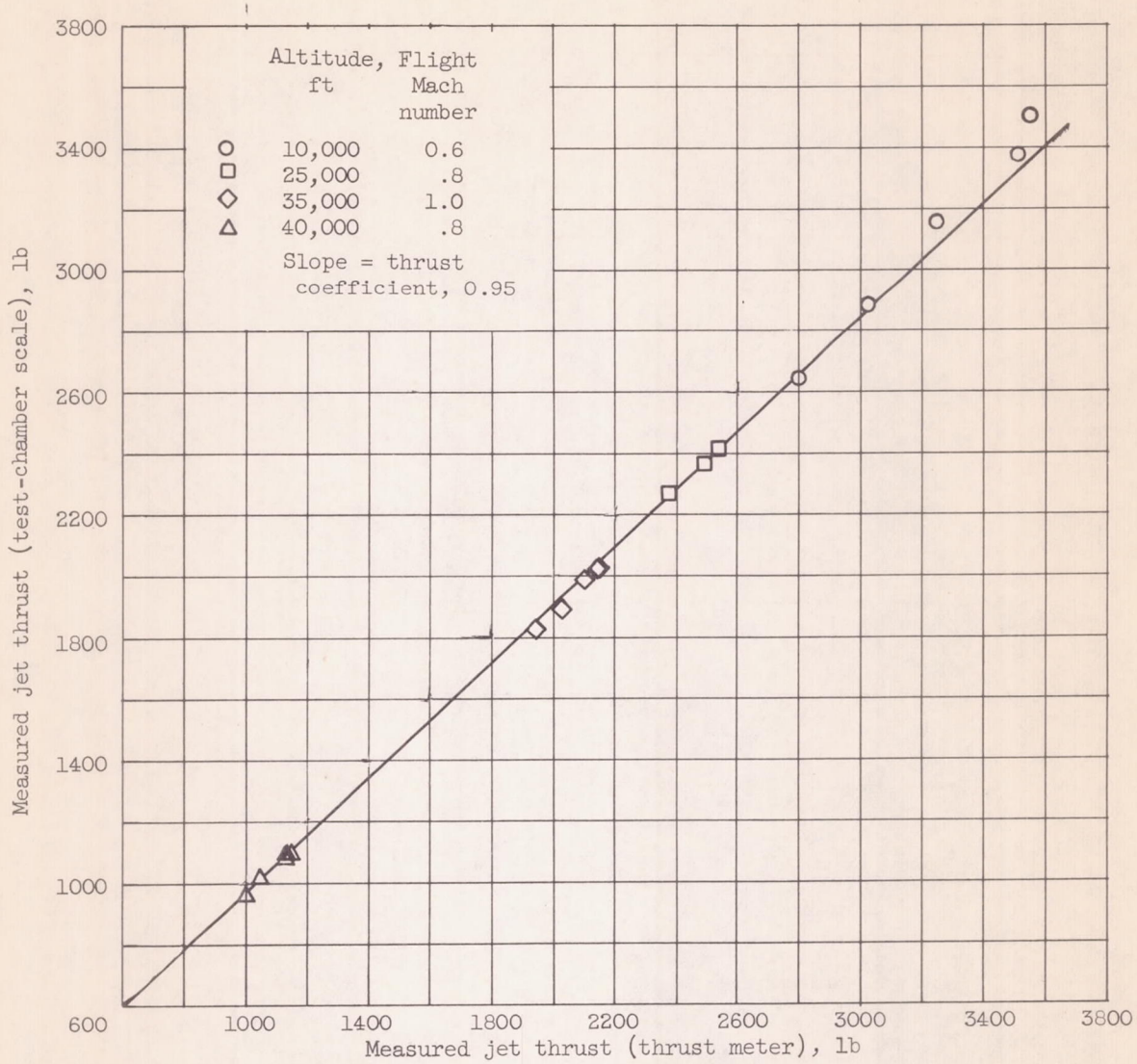

Figure 8. - Comparison of thrust-meter and altitude-chamber thrust-scale measurements.

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